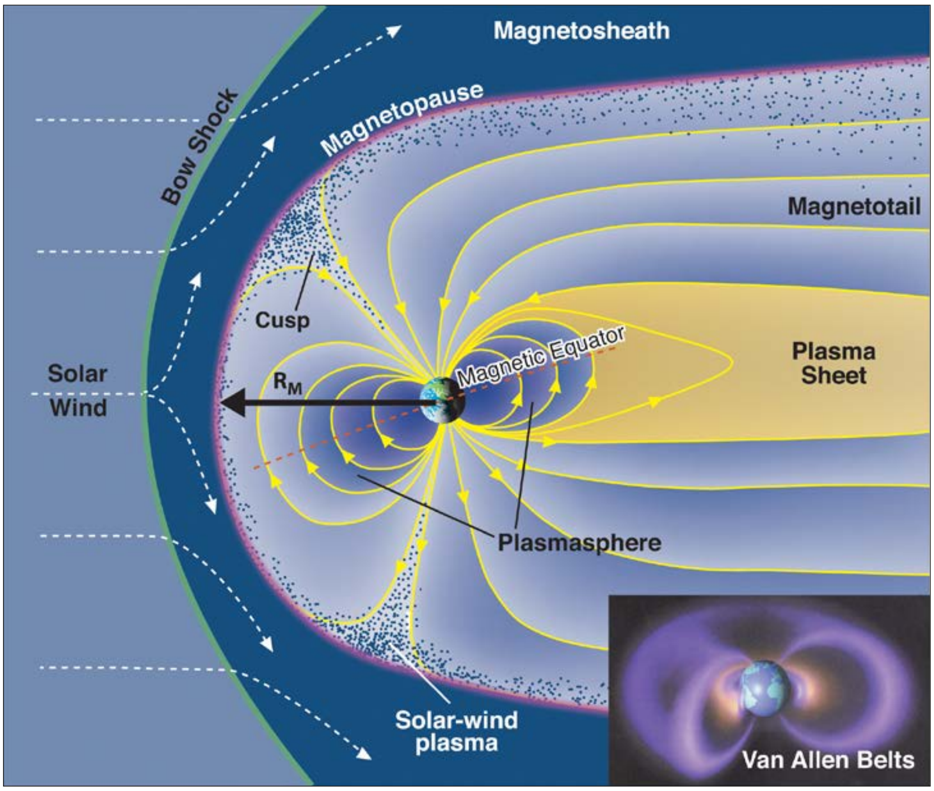
A global view of storms and substorms

Jasmine Kaur Sandhu, **Maria-Theresia Walach**, **Hayley Allison** and **Clare Watt** report on the RAS meeting The Global Response of the Terrestrial Magnetosphere during Storms and Substorms.

Explorations into the geomagnetic field are thought to have begun around the beginning of the 11th century in China, later extending to Asia and Europe (Mitchell 1932) and leading to the discovery of the global nature of the magnetic field reported by Gilbert (1600). Since then, we have identified the highly variable and dynamic nature of the global geomagnetic field in near-Earth space, specifically magnetic storms and substorms (e.g. Graham 1724, Birkeland 1901). Ground-based data led to the proposal of key features of our space environment: the ring current (Stoermer 1910), the plasma-filled magnetosphere (Gold 1959, Chapman & Ferraro 1931) and the solar wind (Parker 1958). These were all later confirmed with the advent of the space age, which also brought the discovery of new features, such as our highly dynamic radiation belts (Van Allen 1958).

In 1961, Jim Dungey proposed a new theory on how our magnetosphere interacts with the solar wind (Dungey 1961) to explain the observed dependence of geomagnetic activity on solar activity (e.g. Sabine 1852). Dungey (1961) proposed the idea of an "open magnetosphere", where coupling between the geomagnetic field and the interplanetary magnetic field (IMF) leads to a large-scale, global, circulatory flow of magnetic field lines and plasma within the magnetosphere. This theory was later confirmed observationally (Fairfield & Cahill 1966, Fairfield 1967), and we now know that the coupling between the solar wind and the magnetosphere creates a dynamical and highly variable system, and is a key driver in generating storms and substorms. Figure 1 shows a simplified schematic of our current understanding of the magnetosphere and the key regions of interest.



1 A schematic illustrating the large-scale structure of the magnetosphere and the key regions. The inset shows the structure of a trapped energetic particle population in the inner magnetosphere, known as the Van Allen radiation belts. (Kivelson & Bagenal 2007)

Storms are characterized by rapid enhancements in the ring current, an electrical current in the inner magnetosphere produced by the net westward drift of ions, where increases in the energy and number of ions results in increases in the ring current intensity. During magnetic storms, large enhancements in the ring current intensity lead to a weakening of the local magnetic field and are also associated with intense radiation belt activity (Gonzalez 1994, Baker *et al.* 2004). On average, storms last several days, with the storm main phase lasting around one day. Geomagnetic storms are highly variable in terms of their intensity, duration and impacts on the inner magnetosphere. A key impact of geomagnetic storms is concurrent radiation belt activity in the inner magnetosphere. The radiation belts have a complex relationship with geomagnetic storms and also exhibit a high degree of variability, shaped by the multitude of energization and loss processes (e.g. Elkington 2013, Reeves *et al.* 2003).

"On average, storms last several days, with the storm main phase lasting around a day"

Substorms

In contrast to storms, substorms have timescales of a few hours. Substorms are characterized by a storage and rapid release of energy by the magnetotail, and are associated with clear auroral signatures and intensifications (e.g. Baker *et al.* 1981). Strong coupling with the IMF leads to a loading of highly stretched open field lines to the magnetotail. Substorm onset is accompanied by rapid magnetic reconnection in the magnetotail, which promptly closes large amounts of flux. The stretched field lines contract to a more dipolar configuration, a considerable amount of energy is released and highly energetic plasma is transported earthwards on the nightside. Intense field-aligned currents drive energetic electron precipitation and result in the intensification, broadening and expansion of the auroral oval (see figure 2).

Although substorms are known to take

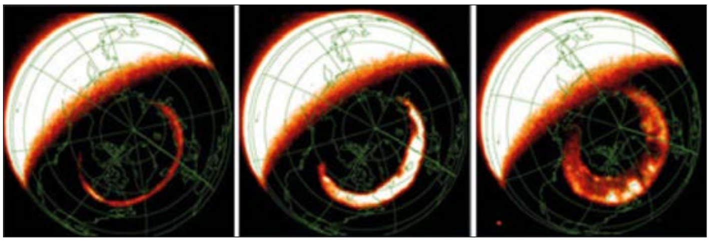
place when the magnetosphere is effectively coupled with the IMF, they are highly variable and unpredictable. Furthermore, because substorms can transport energetic plasma to the inner magnetosphere, it has been proposed that substorms are important in generating geomagnetic storms (Daglis *et al.* 1999a,b). But the role of substorms in storm generation has also been debated by others (Kamide 1979, 1992); the coupling between substorms and storms remains unclear.

The induced currents and magnetic field perturbations mean that the existence of a storm or substorm can be identified from magnetic field observations at ground level. Magnetic field data can be condensed into simple indices that exhibit relatively clear signatures during storms and substorms, and are highly useful in identifying and exploring events (see box "The importance of geomagnetic indices" for further details).

Studies of the magnetosphere, specifically the storm and substorm phenomena, are strongly motivated by the implications of these processes for our everyday lives. Although very intense storms and substorms are rare, when they do occur the ramifications for society are significant (Lanzerotti 2013). The events drive large ground-induced currents (GICs), which can disrupt ground power networks. Changes to the ionosphere can lead to radio-wave absorption and thus communication blackouts. Additionally, geomagnetic storms can have devastating effects on satellites: extreme intensifications of the radiation belt are highly damaging to satellites, and the increased altitude of the ionospheric boundary during storms increases satellite drag for low-orbiting satellites. We need to understand the physical processes associated with storms and substorms, determine why they occur and identify how they affect our magnetosphere. There are many outstanding questions and much remains to be investigated. This was our motivation for holding the RAS Specialist Discussion Meeting "The Global Response of the Terrestrial Magnetosphere during Storms and Substorms" (held at Burlington House on Friday 8 February 2019), where work on understanding storms and substorms was presented and discussed. In this review, we explore the key questions that were raised in the context of existing understanding, the new results presented and the discussions that were had.

How important is variability?

A key discussion topic that arose in the meeting concerned how we extract information about physical processes from trends in magnetic indices. Storms and substorms are highly variable processes and events that reach the same magnitude in a given index can differ greatly in other observed characteristics. For example, two substorms may be associated with the same AL index minimum, but the duration of the bay, the auroral signatures of the substorm, and the impacts on the inner magnetosphere can vary significantly between the two events. Using a single index at a single time to represent the globally averaged magnetic field response cannot capture the large degree of variability in other aspects of the magnetosphere (e.g. solar wind driving and plasma properties). Conversely, for events that seem to have the same level of solar wind coupling and internal conditions, the response of the magnetic indices and the magnetospheric system is wide ranging, in terms of the occurrence and intensity of storms and substorms, as well as steady magnetospheric convection.



2 The northern auroral oval viewed by the IMAGE spacecraft. The thickening and contraction of the auroral oval following substorm onset is apparent. (SWRI)

A fundamental question is: why do we observe so much variability? And what physical magnetospheric processes drive it? **Sarah Bentley** (University of Reading) stressed that it is important to review how we consider the magnetospheric system. Taking a deterministic approach, there must be a process in the magnetosphere or a characteristic of the solar wind coupling that we haven't identified. Alternatively, is it just the chaotic nature of the system that introduces this variability (e.g. Prabin Devi 2013)? This highlights the question of whether we can predict when and how these events occur and identify the source of their variations.

> "The promising potential for predicting super-storms was explored"

In contrast to the seemingly unpredictable qualities of the magnetosphere, work presented by **Sandra C Chapman** (University of Warwick) demonstrated clear reproducible trends in the distribution tails of magnetic indices (including the AA index, Dst index, and AE index), over several solar cycles (Chapman *et al.* 2018). Chapman highlighted that this result was derived from the data only, without restrictions based on knowledge of physical processes and despite each solar cycle varying in duration and peak activity level. By extrapolating this trend, the promising potential for predicting super-storms – to support space-weather climatology – was explored by **Aisling Bergin** (University of Warwick). The reproducibility of extreme storm occurrence provides an avenue into understanding variability in storms. Furthermore, **Heather McCreadie** (University of Warwick) demonstrated how the variations in the Dst index during any storm can be characterized using an autonomous curve-fitting technique. McCreadie's approach in quantifying the Dst index variations during storm suggests important applications in being able to explore variability in the Dst response from storm to storm.

How do we define storms and substorms?

The discussion on how events characterized by the same level of magnetic indices led to discussion of what information on physical processes the indices provide. Is this the information that we need? If not, what is required? And how does the information we have and what we need influence how we define these events?

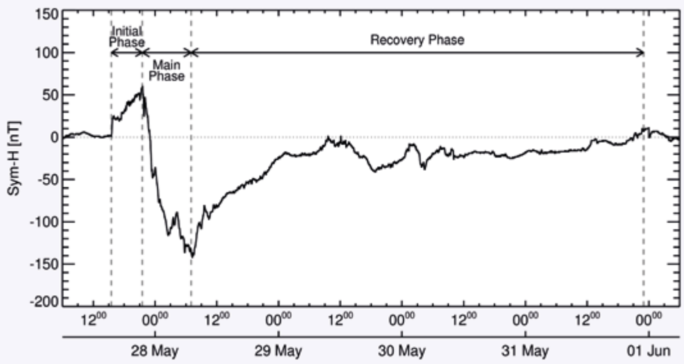
As discussed above, storms and substorms exhibit a high degree of variability associated with different features of the event (e.g. solar wind coupling, magnetic responses, inner magnetospheric response etc). In order to identify how we define the events, we have to choose what is the defining feature of interest. The choice of important feature of a storm or substorm is highly dependent on the "end user", as pointed out by Chapman in the discussion. For example, **Richard Horne** (British Antarctic Survey) discussed how storms driven by coronal mass ejections (CMEs) are associated with a much larger ring current enhancement and magnetospheric compressions than storms driven by corotating interaction regions (CIRs); this means that the former can generate intense GICs. In contrast, the CME-driven storms are associated with a significant inward transport of the radiation belts (unlike the CIR-driven storms), with the result that geosynchronous satellites are no longer within the radiation belts during CME-driven storms, but are located within the radiation belts for CIR-driven storms. Consequently, CIR-driven storms pose a significant hazard for space-based instrumentation and CME-driven storms pose a significant hazard for electrical networks on the ground (Borovsky & Denton 2006). This example highlights the complexity associated with identifying the crucial

The importance of geomagnetic indices

Storms and substorms are associated with significant changes in the magnetospheric plasma and magnetic field, as well as enhanced flows of large-scale electrical currents in the planetary system. Ground-based magnetometers are therefore highly effective at measuring the global magnetic field perturbations from the currents; we see consistent signatures in ground-based magnetometers during storms and substorms.

Since the late 1930s (Bartels *et al.* 1939, Rostoker 1972), magnetic-field data have been condensed into simple indices to indicate the level of geomagnetic activity. The Dst index and the Sym-H index are derived from magnetometers that map to the ring current region and consequently experience significant north–south deviations during magnetic storms (e.g. Sugiura & Kamei 1991). A typical signature of a geomagnetic storm in the Dst or Sym-H index is shown in figure 3.

Substorm activity can be encapsulated by the auroral electrojet indices (AE, AL and AU) based on high-latitude ground magnetometer data (Davis & Sugiura 1966). Characteristic "bays" in the AL index during a substorm is typically observed. On average, we see a clear signature in the indices for storms and substorms that agree well with the typical traces.



3 An example of the Sym-H trace for a typical storm.

This is the basis for the identification of storms and substorms from the traces of magnetic indices; and there exist a multitude of techniques to extract events from index data (e.g. Newell & Gjerloev 2011, Turner *et al.* 2015, Forsyth *et al.* 2015, Murphy *et al.* 2018). The variety of techniques in use highlights the fact that it is not trivial to identify events; this arises predominantly from the large degree of variability within storms and substorms.

feature of the storm; this can depend on the "end user" needs.

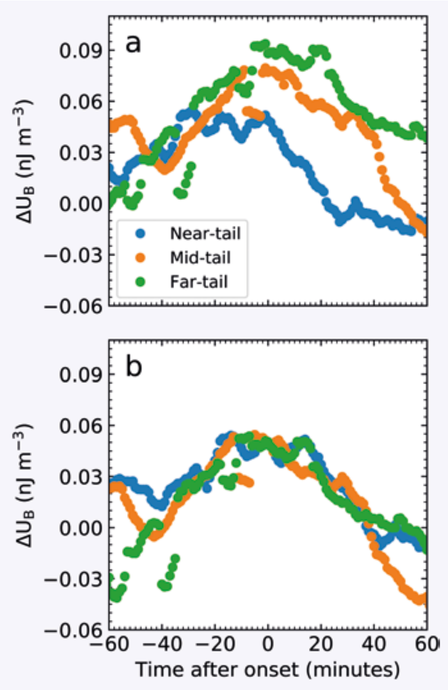
The "end user" problem also has implications for what we consider to be "big" or "small" events. Many storms and substorms are categorized by the ring current and auroral electrojet indices, respectively, defining events that are above a certain threshold and attributing their size to the peak magnitude of the index. We know that the magnetic indices only describe one part of the system and can conceal a wealth of information. The keynote talk by **Elena Kronberg** (Max Planck Institute for Solar System Research) highlighted the implications of magnetospheric composition, describing how heavy ions during storms and substorms play an important role. Particularly, the presence of heavy ions can contribute significantly to the total ring current energy (Kronberg *et al.* 2017). The radiation belts are also a key component of magnetospheric dynamics and work by **Colin Forsyth** (Mullard Space Science Laboratory, University College London), for example, demonstrates different degrees of radiation belt enhancement from the substorm process. In contrast, GICs have been demonstrated to be significant during storms and substorms, as highlighted by **Neil Rogers** (Lancaster University) who examined drivers of these extreme magnetic field fluctuations. Overall, it is clear that it is difficult to assess the size of a storm or substorm, without first prioritizing whether the "end user" is most interested in ion composition, radiation belt enhancements, GICs, radio-wave absorption in the ionosphere etc.

Using a threshold to define storms and substorms with magnetic indices also highlights some key issues. The threshold is often chosen to distinguish clear events from background fluctuations in the indices. Although this is a reasonable and practical option, it inherently neglects the smallest events and prohibits our understanding of how storms and substorms vary across all magnitudes. We do not yet have a clear understanding of how small a storm or substorm can be. This highlights a significant lack of knowledge of what a storm or substorm actually is; current methods simply define the events as a deviation from background variations in a magnetic index. Improvements in defining the events then rely on understanding the key physical processes: what triggers the events and why?

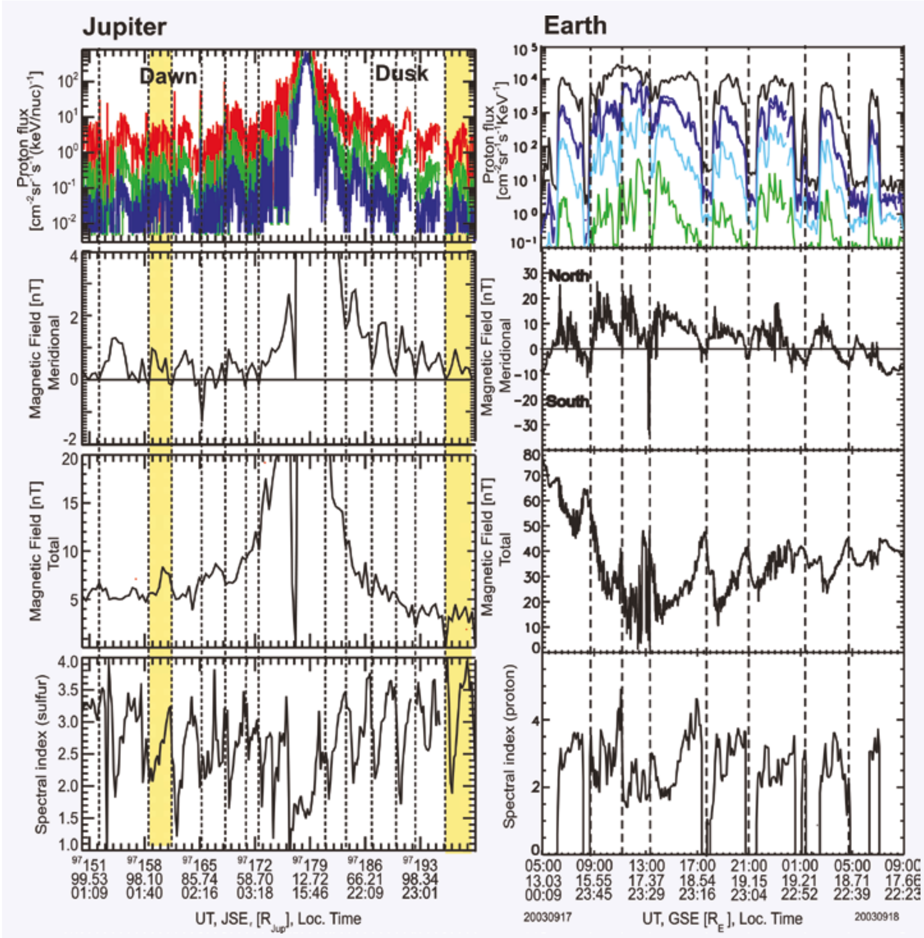
Why do substorms occur?

Current literature presents a divided view on substorm initiation, largely focusing on two key theories. The near-Earth neutral line (NENL) model proposes the formation of a neutral line in the magnetotail at approximately 25 Earth radii (R_E) (Baker *et al.* 1996). The loading of the magnetotail with open flux during the substorm growth phase results in the thinning of the tail current sheet, which continues until a threshold is reached. Magnetic reconnection of the tail field lines is triggered at the neutral line, leading to the dipolarization of field lines and current divergence along them. The NENL model is commonly referred to as the "outside-in model", because the disturbance originates in the tail as a result of reconnection and initiates the current disruption closer to the Earth, at approximately 10 R_E. Conversely, the cross-field current disruption (CD) model, also proposed to explain the substorm initiation process (Lui 2015), suggests that plasma instabilities in the near-Earth region act to disrupt the current sheet and trigger reconnection of field lines downtail. This is known as the "inside-out model".

Present understanding of substorm initiation cannot determine when either the NENL or CD model is applicable and no consensus has been reached. But this meeting exhibited work that indicates progress in unravelling the substorm initiation process. The meeting included a presentation from **John Coxon** (University of Southampton), who investigated energy propagation through the magnetotail during the substorm process. Using Cluster observations of the magnetospheric lobes, Coxon demonstrated that following substorm onset, energy density signatures are first observed in the near-Earth magnetotail and then propagate downtail on timescales of approximately 20 minutes (figure 4) (Coxon *et al.* 2018). The results suggest that substorms are triggered in the near-Earth magnetosphere with the disturbance propagating downtail, in accordance with the CD model. Work presented by **Andy Smith** (MSSL, UCL) also investigated the substorm initiation process using *in situ* observations. Smith used THEMIS observations to understand the characteristics of plasma instability-driven waves associated with the substorm onset process (Kalmoni *et al.* 2018). Smith's work presents a promising avenue into understanding how and when near-Earth plasma instabilities are responsible for substorm initiation.



4 (a) Variations in the energy density, binned for downtail distance in the magnetotail, and plotted relative to substorm onset. The signatures are first seen in the near-tail, and seen latest in the far-tail suggesting that the disturbance propagates tailwards. (b) The data shown in (a) are time lagged so that the plateaus centre on substorm onset. (Coxon *et al.* 2018)

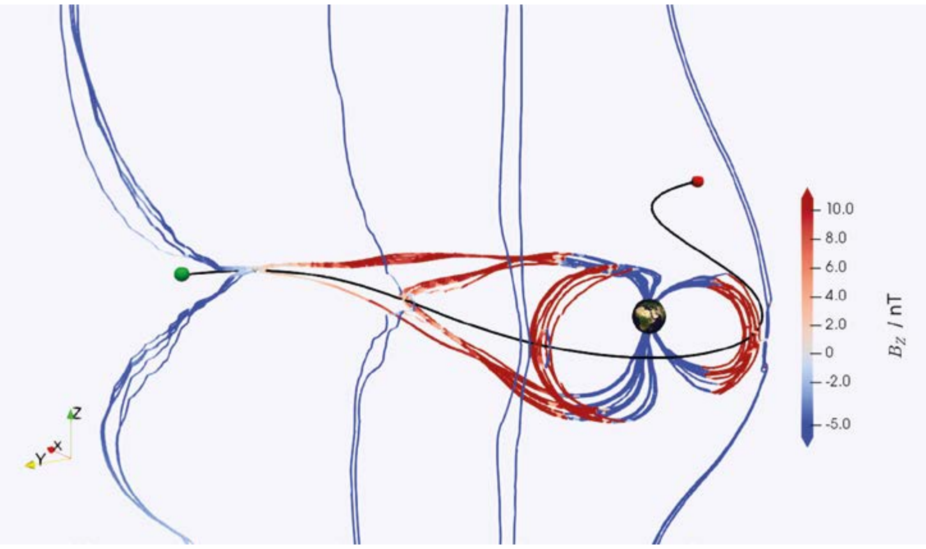


5 A comparison of proton flux (first panel), magnetic field (second and third panels), and energy spectral index (fourth panel) during sawtooth events at Jupiter (left) and Earth (right). Periodic loading and field stretching is observed for both systems, with the times of dipolarizations indicated by the vertical dashed lines. (Kronberg *et al.* 2008)

As well as understanding how substorms are triggered, another key area of active research includes understanding why different types of substorms are observed and the drivers of these events. One type of substorm activity is periodic substorms, also known as sawtooth events. Sawtooth events are sharp enhancements and slow decays of energetic particle fluxes in the inner magnetosphere occurring periodically with a consistent periodicity of approximately three hours (e.g. Borovsky *et al.* 1993). The events are associated with dispersionless injection events driven by magnetospheric dipolarization, attributed to substorms (e.g. Huang *et al.* 2003). Kronberg referred to periodic substorm-like events observed at Jupiter, which are tail reconnection events accompanied by auroral activity and periodic energetic flux dropouts, and have a periodicity of approximately three days (Radioti *et al.* 2008). These events are thought to be internally driven, primarily arising from internal magnetospheric mass loading from Io's plasma outflows. The relatively constant rate of mass loading imparts an approximately stable periodicity to the field-line stretching and consequent tail reconnection (Vasyliūnas 1983). Kronberg proposed that relatively constant mass loading from auroral outflows affects the magnetosphere in a similar way to Io's outflows at Jupiter. The internal mass loading leads to field-line stretching and drives periodic substorms, resulting in sawtooth events (figure 5) (Kronberg *et al.* 2008). She emphasized the need for observational studies to investigate the role of internal mass loading further, and the discussion highlights a key area of future research.

Steve Milan (University of Leicester) highlighted work showing that substorm activity can be categorized by the auroral onset latitude and suggested two distinct types of substorm activity: substorms associated with high-latitude onsets and substorms associated with low-latitude onsets. Previous work has demonstrated that this distinction is associated with a range of differences including ionospheric convection (Grocott *et al.* 2009), auroral intensity and inner magnetospheric conditions (Milan 2009). Milan demonstrated a further key difference, namely that substorms associated with a high-latitude onset and prolonged dayside driving are likely to be followed by a period of steady magnetospheric convection (SMC), in agreement with the results of Walach and Milan (2015). In contrast, substorms with a low-latitude onset are more likely to exhibit multiple onsets, such as sawtooth events, and no SMC. Milan attributed this feature to the characteristics of the ionosphere and its significant role in the coupling process. He proposed that enhanced ionospheric conductance in the auroral bulge for low-latitude substorms inhibits convection, leading to an accumulation of flux and a reduction in nightside reconnection. This prevents an SMC episode and instead allows the magnetosphere to enter the loading phase of a subsequent substorm.

Understanding the conditions under which substorms occur and the drivers of the activity provides valuable insight into how we can forecast and predict their occurrence (Eastwood *et al.* 2017). A comment by Richard Horne highlighted how our understanding of the conditions prior to substorms can be highly useful in forecasting techniques. He argued that it may be more feasible to predict these conditions, which are probably associated with substorms, than predict the occurrence of a substorm itself. For example, work by **Robert Shore** (British Antarctic Survey) demonstrated how, using a machine-learning approach applied to ground magnetometer data, clear and distinct signatures are associated with sawtooth and substorm events. Shore identified that although the precursor signatures of sawtooth compared to substorms events differ in magnitude, the



6 A Gorgon MHD model simulation of the distorted dayside separatrix (black line) during storm onset. The B_z component of the field lines is shown by their colour, and the dawn and dusk null points are indicated by the green and red spheres, respectively. (J Eggington)

structure is essentially the same. Furthermore, **Maria-Theresia Walach** (Lancaster University) presented an analysis of ionospheric convection observations from the Super Dual Auroral Radar Network (SuperDARN) and showed clear dependences and features associated with solar-wind driving and geomagnetic events. These results demonstrate how consistent signatures can be identified routinely and can be incorporated into forecasting techniques; they also reinforce the need for ionospheric observations at mid-latitudes due to the convection pattern expanding.

Work by **Micheala Mooney** (MSSL, UCL) presented some insight into current forecasting capabilities. Mooney and colleagues assessed the performance of the OVATION Prime-2013 model, which forecasts the probability of observing auroral precipitation in polar regions (Newell *et al.* 2014). They determined that, although the OVATION model performs well in distinguishing the spatial characteristics of aurora occurrence, it largely under-predicts the probabilities of aurora occurrence. An advanced understanding of how the magnetosphere couples with the solar wind and generates aurora is needed to shed light on how we can better forecast auroral precipitation. This example demonstrates that current endeavours into forecasting space weather are significant, but continued investigation into understanding the conditions associated with geomagnetic events will be invaluable for further progress.

Solar wind drivers

As well as investigating the magnetospheric conditions associated with substorms, it is essential to understand the key driver of activity: the solar wind. The meeting discussed intensive efforts to explore solar wind properties and how the solar wind couples to our terrestrial magnetosphere. Of particular interest were results presented by **Téo Bloch** (University of Reading), whose new solar wind classification scheme based on machine-learning techniques identifies periods of coronal-hole wind and streamer-belt wind. Previous work has shown that the magnetosphere response is significantly different for these two drivers (e.g. Borovsky & Denton 2006), so being able to categorize the type of driving is essential information. Furthermore, an automated technique suggests significant applications for forecasting methods.

"It is essential to understand the key driver of activity: the solar wind"

Another important form of variability in the solar wind occurs on solar wind cycle timescales, as highlighted in a comment by Sandra Chapman. The solar wind cycle imparts long-term variations in geomagnetic activity (e.g. Richardson & Cane 2012), and thus it is important to consider these trends. For example, **Andrei Samsonov** (MSSL, UCL) assessed the long-term variations in the magnetopause position, as well as the level of geomagnetic activity. In particular, differences between solar cycles can have marked differences in the magnetopause standoff distance. Samsonov reported that the magnetopause standoff distance increased by more than 2 R_E for one solar cycle compared to the next, due to long-term trends in solar activity.

Understanding the details of how the magnetosphere couples to the solar wind is non-trivial. However, **Joseph Eggington** (Imperial College London) demonstrated that magnetohydrodynamical (MHD) modelling has significant potential for investigating the relationship. Using the Gorgon MHD code (Ciardi *et al.* 2007), Eggington reproduced the coupling between the solar wind and the magnetosphere, identifying the locations of reconnection (figure 6). This information on where and when reconnection happens is crucial in understanding how energy and flux can propagate through the magnetospheric system. Specifically, it provides details on how flux can be added to the magnetotail during substorm growth phases, where the flux is closed on the nightside, and when the flux closure occurs allowing energy to propagate to the inner magnetosphere.

The solar wind–magnetosphere coupling is a primary factor in driving heavy ion outflows from the high-latitude ionosphere, which can then convect throughout the magnetosphere (e.g. Yau & André 1997). As highlighted by Kronberg, the presence of heavy ions in the magnetospheric plasma can dramatically alter the dynamics of the magnetosphere. For example, Oullette *et al.* (2013) show that heavy ion outflows can significantly alter the mass density and pressure in the magnetotail, leading to the formation of a new neutral line for reconnection. Furthermore, heavy ion concentration in the inner magnetosphere is a key factor in the local plasma mass density, thus controlling the Alfvén speed and the way that energy propagates through the system (e.g. Sandhu *et al.* 2017, 2018a).

Inner magnetosphere during substorms

Substorms are associated with a major redistribution of energy within the magnetosphere; understanding how this energy is partitioned is a key outstanding question. Specifically, we need to understand whether the substorm process can provide the inner magnetosphere with energetic particles and generate geomagnetic storms, and whether the injected particles can provide a seed population for radiation belt energization.

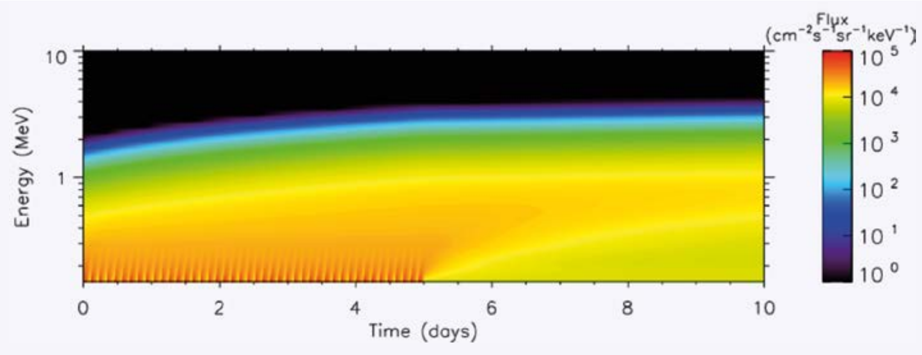
Harneet Sangha (University of Leicester) presented an investigation into field-aligned current signatures, in particular sub-auroral polarization streams (SAPS). The SAPS observations were attributed to the presence of substorm-injected plasma in the inner magnetosphere generating partial ring currents that divert along field lines into the ionosphere. Results from **Lauren Orr** (University of Warwick) demonstrated the large-scale magnetic response of the system to substorms. Based on data from more than 100 magnetometer stations in the SuperMAG array, Orr used a dynamical directed network to determine the characteristics of current systems. The results from Sangha and Orr provide insight into how energy propagates through the inner magnetosphere following substorm onset, through the development of large-scale current systems mapping to the ionosphere.

Understanding how particles can access the inner magnetosphere can also be advanced through the use of global MHD models. **Ravindra Desai** (Imperial College London) used the Gorgon MHD model, combined with the Integrated Van Allen Radiation Belt (IVAR) model, to simulate the inner magnetosphere response to extreme space weather. An injection of highly energetic particles into the inner magnetosphere was observed. Desai showed that these particles can be injected onto closed drift paths, adding to the trapped populations. But the highly distorted magnetosphere leads to losses for other particles on open drift paths, and the magnetopause distortion also results in the bifurcation of particle drift paths.

The meeting highlighted the significance of continued substorm activity, as opposed to a single isolated substorm event. Colin Forsyth demonstrated that the effect of a single substorm on the radiation belts is highly variable; only 50% of substorms result in an increase in the radiation belt population. The radiation belts respond to geomagnetic storms with a high degree of variability (e.g. Reeves 1998). However, work presented by Horne highlighted that it may be the duration of substorm activity that is crucial for driving radiation belt enhancements. Horne demonstrated that the occurrence of multiple substorm onsets provided the necessary sustained substorm injection activity that allows time for wave energization (figure 7). In terms of the ring current population, work presented by **Jasmine Sandhu** (MSSL, UCL) quantifies the substorm associated energization of ring current ions (Sandhu *et al.* 2018b), and demonstrates that the characteristics of substorms associated with continued activity are also conducive to enhancing the inner magnetosphere compared to isolated events. Additionally, **Yulia Bogdanova** (Rutherford Appleton Laboratory) presented significant results on the storm/substorm relationship. Bogdanova assessed correlations between geomagnetic indices and demonstrated a poor correlation between extreme storms and substorms; the result suggests that the magnitude of substorms is not a key factor in shaping storm activity and that the relationship is more complex. The work presented at this meeting suggests that the duration of substorm activity, as opposed to its strength or magnitude, could be the key factor in energizing the inner magnetosphere.

The inner magnetosphere during storms

As well as considering the generation of geomagnetic storms, the meeting also discussed the implications of geomagnetic storms, including how the radiation belts are energized and depleted during storms.



7 Modelled flux enhancements under a five-day period of fast solar wind with substorm injections, followed by a five-day period of low activity. The results show acceleration to high (>2 MeV) energies, which persist for days. (R Horne)

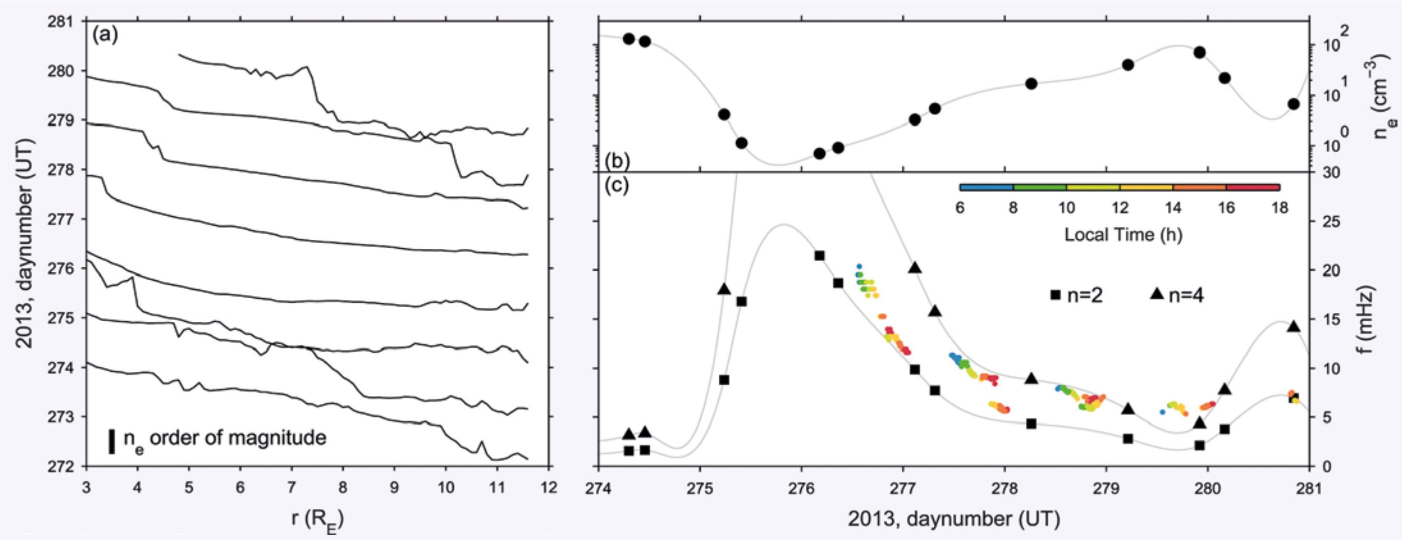
A key route of energy transfer in the inner magnetosphere is through the propagation of MHD waves, which can significantly energize the radiation belt population through wave–particle interactions. Work by **Jonathan Rae** (MSSL, UCL) and **Martin Archer** (Queen Mary University of London) explored the properties of ultra-low frequency (ULF) waves, which can couple to geomagnetic field lines and form large-scale standing waves. The frequencies of these standing waves – the eigenfrequencies – and their spatial variations are a crucial factor in controlling how waves can propagate in the inner magnetosphere. Rae used ground-based magnetometer observations of wave power and eigenfrequencies to monitor storm-time variations. A case study demonstrated that dramatic variations in the magnetic field configuration and the presence of heavy ions drove significant variations in the eigenfrequencies, and thus allowed for an increased accessibility of wave power to the inner magnetosphere. In contrast, Archer presented spacecraft observations of ULF waves using a novel sonification technique combined with a citizen-science approach (Archer *et al.* 2018). Similarly, changes in the inner magnetospheric plasma conditions, attributed to plasma refilling in the storm recovery phase, were observed to impart variations in the ULF wave properties (figure 8). Our understanding of ULF wave properties are furthered by the probabilistic model of ULF wave power based on 15 years of data developed by Sarah Bentley. Her model provides significant insight into the variability associated with these waves, and the importance of wave processes during geomagnetic storms.

"The magnetopause is significantly closer to the Earth than shown in previous models"

In terms of the radiation belts, the meeting hosted a broad examination of how electron fluxes vary in response to a wide variety of storm-related processes. Storms exhibit dramatic variations in electron fluxes, including drop-out events and energizations. Work by **Hayley Allison** (British Antarctic Survey/University of Cambridge) showed how, after a flux drop-out event, a seed population of electrons in the inner magnetosphere can be effectively energized by chorus waves and redistributed by radial diffusion. These results demonstrate how these processes can act to rebuild the terrestrial radiation belts. Furthermore, the effects of radial diffusion were investigated by **Rhys Thompson** (University of Reading), providing valuable information into how diffusion can be characterized. Thompson suggested a probabilistic approach, as opposed to the commonly used deterministic models, allowing for a clearer understanding of variability in diffusion rates.

The loss process of radiation belts during geomagnetic storms were also considered. **John Ross** (British Antarctic Survey) examined relativistic electron decay in the radiation belts arising from plasmaspheric hiss and very-low-frequency transmitter waves. **Frances Staples** (MSSL, UCL) presented results based on spacecraft observations of magnetopause crossings, and identified that changes in the position of the magnetopause during the storm is significant for radiation belt loss. Staples demonstrated that the magnetopause is significantly closer to the Earth than shown in previous models, which has led to underestimations of magnetopause losses.

From an MHD modelling approach, **Lars Mejnertsen** (Imperial College London) applied a Gorgon MHD model to simulate the behaviour of the whole magnetosphere during a Carrington-level storm. In addition, Mejnertsen examined the resulting ground-induced currents and explored how the response varies with different internal magnetic field conditions. The work highlights a consideration into long-term changes in the internal geomagnetic field and how this can impart variations in how the magnetosphere behaves during storm times.



8 (a) Electron density profiles observed by THEMIS and (b) electron density at geosynchronous orbit. (c) The estimated eigenfrequencies based on density observations are shown in black and observed eigenfrequencies are shown by the coloured points, for both the 2nd (squares) and 4th (diamonds) harmonics. The observations taken during the recovery phase of a geomagnetic storm are shown, and the results indicate that plasmaspheric refilling drives a decrease in eigenfrequencies. (Archer *et al.* 2018)

Key outcomes

The meeting raised several key questions for the community, as well as highlighting the broad array of excellent work underway. To conclude this review, we summarize the key outstanding questions:

- Can we account for the large degree of variability observed in the magnetospheric system?
- How should we define storms and substorms?
- Is continued substorm activity a key proponent in generating geomagnetic storms?
- What is the role of the inner magnetosphere, including the presence of heavy ions, in shaping storms and substorms?

Through formal and informal discussions, it is clear that no part of the system can be ignored when considering geomagnetic storms and substorms. These phenomena involve multiple aspects of solar wind–magnetosphere–ionosphere–thermosphere coupling: there is no single dataset or model that can currently describe storms and substorms comprehensively. This meeting highlighted the importance of regularly bringing the community together in order to share the latest results and provide a system-level overview.

The meeting also highlighted key avenues of progress in the field. The capabilities of MHD models, for example the Gorgon MHD model, suggest significant potential in exploring the large-scale transfer of energy and reconfiguration of the system in response to solar wind driving and extreme events. Furthermore, the exploitation of high-quality data from long-term missions such as Cluster, the Van Allen Probes, THEMIS and AMPERE, together with key ground-based remote-sensing facilities such as SuperMAG and SuperDARN, has allowed significant advances in the systematic exploration of the magnetosphere. This is further enhanced by promising advances in data analysis techniques, including machine-learning approaches. Unravelling these problems relies on a continuation of these approaches, fully exploiting available observational datasets, as well as looking forward to future opportunities. Of particular interest to this community is the ever-expanding SuperDARN network, which has in recent years allowed better observations during storms due to increasing mid-latitude observations, as well as the upcoming SMILE mission. ●

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